

# Inertial fusion energy development: what is needed and what will be learned at the National Ignition Facility

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This article was submitted to  
International Forum on Advanced High Power Lasers and  
Applications, Suita, Osaka, Japan, November 1-5, 1999

*U.S. Department of Energy*

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National  
Laboratory

**October 21, 1999**

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# Inertial fusion energy development: what is needed and what will be learned at the National Ignition Facility

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## ABSTRACT

Successful development of inertial fusion energy (IFE) requires that many technical issues be resolved. Separability of drivers, targets, chambers and other IFE power plant subsystems allows resolution of many of these issues in "off-line" facilities and programs. Periodically, major "integrated" facilities give a snapshot of the rate of progress toward the ultimate solutions. The National Ignition Facility (NIF) and Laser Megajoule (LMJ) are just such integrating facilities. This paper reviews the status of IFE development and projects what will be learned from the NIF and LMJ.

**Keywords:** inertial fusion energy, lasers, solid-state lasers, inertial fusion targets, KrF lasers, heavy-ion beams, fusion energy development

## 1. INTRODUCTION

The National Ignition Facility (NIF) in Livermore, California, and the Laser Megajoule (LMJ) near Bordeaux, France, are designed to achieve fusion ignition and modest energy gain. *Figure 1* shows construction activities on the NIF at Lawrence Livermore National Laboratory (LLNL). We are currently reassessing how to bring the NIF on line; there will be some delay and increased costs, but there is strong will to complete the NIF Project. The NIF and LMJ are being built for national security missions. They will provide data to allow the scientists in each country to continue to verify the safety and reliability of stockpiled nuclear weapons in the absence of nuclear testing. An important second mission of the NIF is to contribute to the development of inertial fusion as an energy source. In fact, both facilities will provide technology, experience, and data that will be useful to IFE development whether it was developed explicitly for IFE or for any other mission.

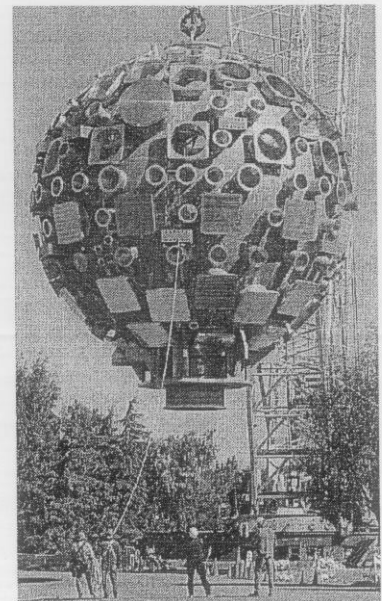
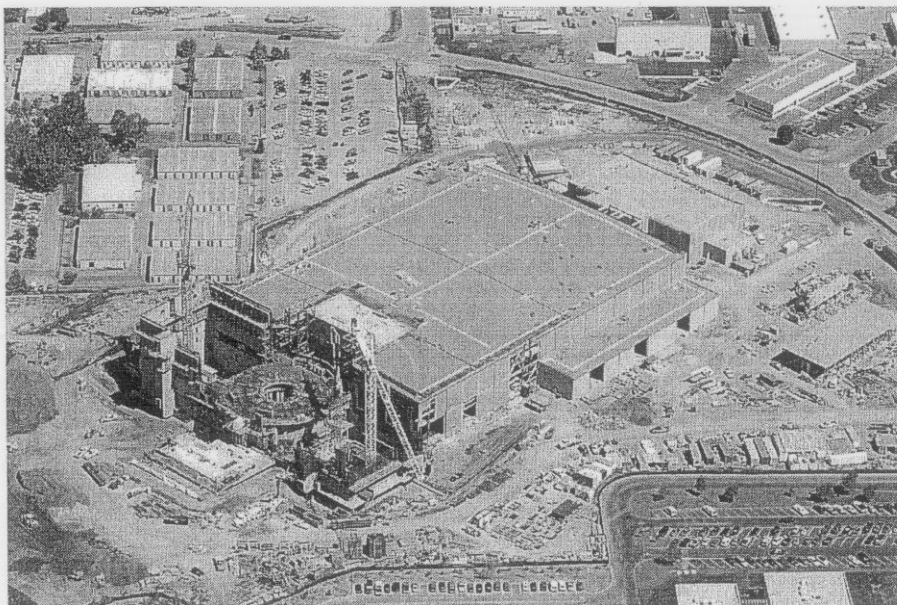


Figure 1. Aerial view of the NIF (left photo) taken April 23, 1999, showing the nearly complete Optics Assembly Building (upper right), the complete shells of the laser bays, and the half-complete concrete structure of the target area building (lower left). The 10-m-diameter Al target chamber (right photo) was set into place in the target area building after a dedication ceremony June 11, 1999, featuring Secretary of Energy W. Richardson.

The NIF is comparable in size, complexity, and cost to a nuclear power plant. To illustrate this graphically, *Figure 2* shows four "nuclear cores" drawn to the same scale. The first is the core of an advanced pressurized water reactor. The second is the NIF target chamber. The third and fourth are the reaction chamber concepts for two IFE power plant studies, Sombrero (a

laser/direct-drive design), and HYLIFE-II (a heavy-ion/indirect-drive design). Many of the issues that would be faced in design, construction, and operation of an IFE power plant are being faced in constructing the NIF.

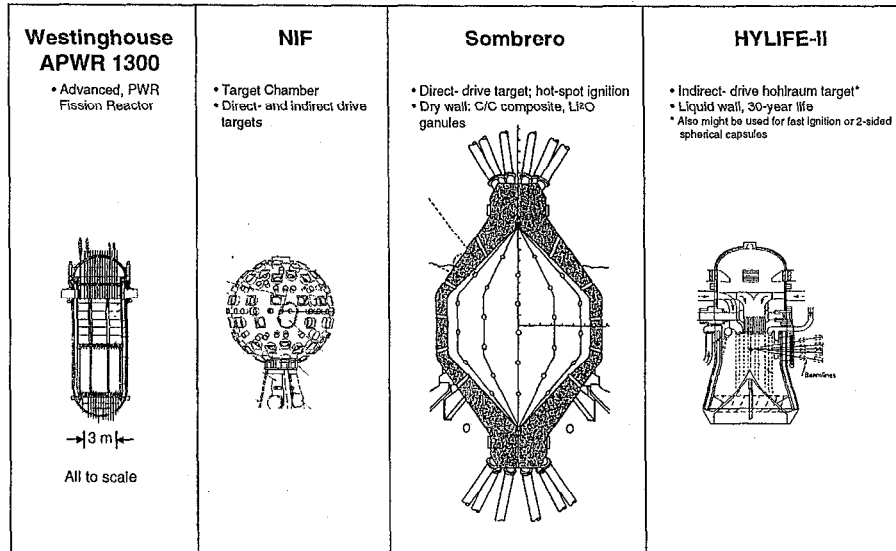


Figure 2. The NIF's target chamber is comparable in size and complexity to a nuclear reactor core and to designs of IFE power plant reaction chambers.

## 2. INERTIAL FUSION ENERGY DEVELOPMENT

To build and sustain support for the development of fusion energy, the community must show that a fusion power plant will be competitive with other forms of energy. It must be competitive from all viewpoints, including, for example, economics, safety, environmental impact, reliability, maintainability, political issues such as nonproliferation, licensing issues, waste disposal, spin-off applications, and affordability of the development program. IFE is a potentially attractive approach to fusion energy on all counts, and the NIF construction project has addressed all the same issues. The basics of IFE and how an attractive power plant can be developed have been described in a number of places.<sup>1,2</sup> The leading candidates for a power plant in the U.S. program are a heavy-ion driver with indirect-drive targets and a laser driver (either KrF or diode-pumped solid-state) with direct-drive targets. In the near term, IFE needs several demonstrations: (1) target ignition and propagating burn at low drive energy (i.e., cost), (2) plausible performance (e.g., pulse rate, efficiency, beam brightness) of one or more IFE power plant driver concepts, and (3) plausible performance of target area systems for operation at 5–10 Hz. These demonstrations will require many separate component developments and a few integrated experiments.

In today's constrained governmental spending for research using "discretionary" funds, having an affordable development path is of paramount importance. If the community cannot obtain large increases in funding for fusion energy development, we must ask ourselves if and how development questions can be answered with smaller annual budgets. IFE may have an affordable development path resulting from:

- The separability and modularity of components and systems.
- The breadth of possible attractive options in targets, drivers, and chambers.
- The leverage from other applications of inertial confinement fusion (ICF) technology such as those in national security, high-energy physics, and industry.
- The fact that engineering development of power plant chambers can be done in scaled, lower-cost reaction chambers.<sup>3,4</sup>

Separability and modularity of components and systems allow international collaborations in which different countries take the lead in off-line development of various components and allow step-by-step upgrades of major integrated test facilities. The plethora of technical options also allows side-by-side development and flexibility to alter the composition of the integrated facilities without starting from scratch each time. Progress in target physics has been steady, supported in the United States, France, and the United Kingdom (and presumably in China and Russia) for national security purposes. Accelerator technology is furthered by the high-energy physics community, and lasers are being developed by industry for

other purposes. The fourth point above allows answering engineering questions in low-power (and, therefore, less costly) facilities rather than in high-power ones.

Given the progress in the field and the attractive features of IFE, a development plan has been formulated by the U.S. fusion energy community.<sup>5</sup> If funded and successful, this program would lay the technical foundation for beginning construction of an engineering test facility (ETF) in the second decade of the next century. The goal of an ETF would be to demonstrate engineering and economic feasibility at the integrated component level.<sup>6</sup>

The IFE “road map” that has resulted from this effort is shown in *figure 3*. This figure shows the different stages of development and demonstration—concept exploration, proof of principle, performance extension, and fusion energy development (the ETF) leading to a demonstration plant. To progress to higher, more costly stages, specific scientific and technical objectives must be met. The existing ICF program engages the road map at the first three levels, with significant ongoing investment by the Department of Energy’s (DOE’s) national security program (illustrated by the shaded region in the performance extension stage). Examples of activities in the first level include exploring ways of extending the successful Z-pinch efforts into an IFE concept (repetition-rate, stand-off, waste stream), examining the high-gain ( $G > 200$ ) “fast-igniter” concept in which compressed fuel is ignited by a separate high-intensity driver, and exploring high-gain ( $G > 100$ ) indirect-drive target concepts with lasers. Examples of the second stage include the development of heavy-ion accelerators at Lawrence Berkeley National Laboratory and LLNL, high rep-rate ( $>5$  Hz) 100-J class KrF (the Electra project at the Naval Research Laboratory), and diode-pumped solid-state lasers (Mercury project at LLNL).

The third stage includes the demonstration of ignition and gain on the NIF and LMJ and the construction of high rep-rate, multikilojoule ( $\sim 15$  kJ to 300 kJ) drivers that also address key chamber issues (driver/chamber interface, beam propagation in the chamber, etc.). Because of these system objectives, these facilities have been named integrated research experiments (IREs).

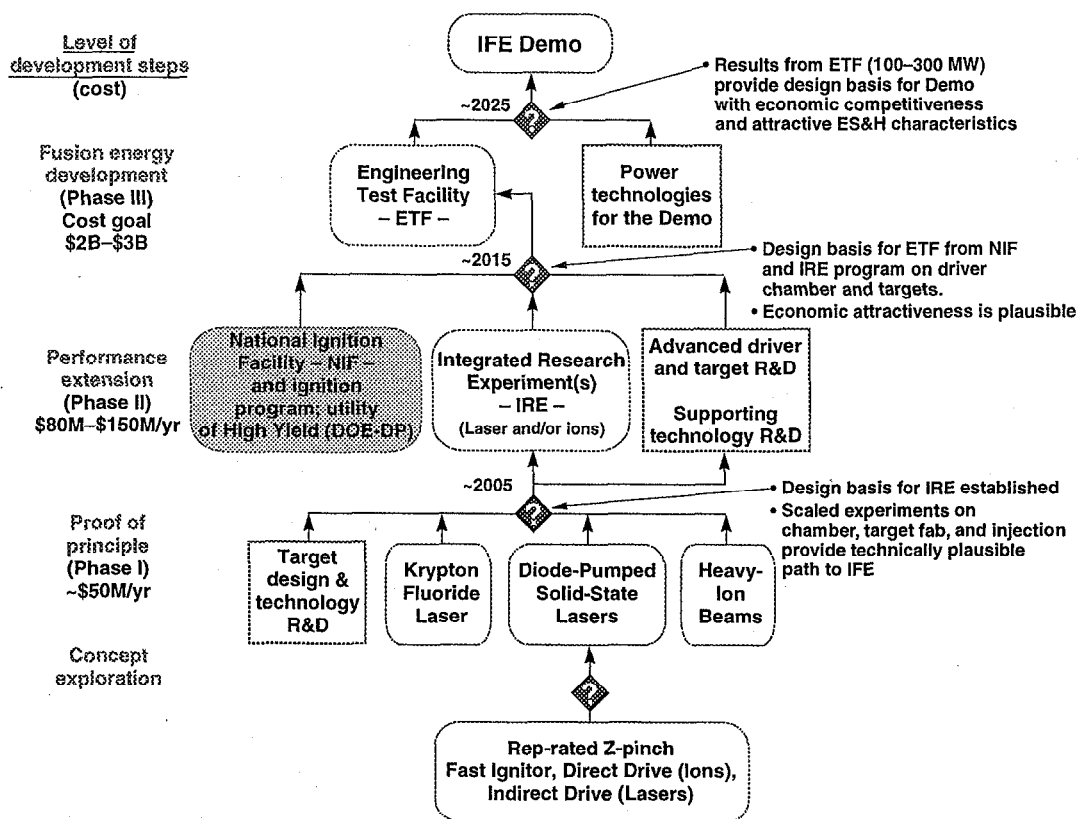


Figure 3. An affordable IFE development plan is illustrated in the IFE “road map.”

The data from the IREs and the target physics and other data from the NIF would form the basis of proceeding with an ETF. In the ETF, a power-plant-scale, high-pulse-rate driver would drive a series of reaction chambers of various designs to

demonstrate the ability of different concepts to operate at 5–10 Hz. In an IFE power plant, the product of rep-rate and capsule yield determine fusion power. These variables are independent. Therefore, reaction chambers scaled down to the size consistent with lower-yield (by a factor of ten) targets could test the ability to achieve the necessary rep-rate.<sup>3</sup> These low-power chambers would be much less expensive. Separately, experiments in a single-pulse chamber could demonstrate the high yield necessary to obtain a driver efficiency/target gain product greater than about ten, a necessary condition for IFE power plant economics.<sup>1</sup> Significantly, the target yield necessary to do the high-rep-rate demonstration will have already been demonstrated on the NIF. One estimate for the cost of an ETF is \$2–3 billion.<sup>7</sup>

Finally, if the ETF is successful, an IFE demo could be built. Depending upon the outcome of the ETF experiments, it may only be necessary to add a high-power reaction chamber to the driver and target factory built for the ETF, to close the tritium and target materials cycles, and to add electricity-producing systems. This development path would be more affordable than one that requires completely separate high-power facilities at each stage.

### 3. THE NATIONAL IGNITION FACILITY AND LASER MEGAJOULE

Demonstration of the critical features of ICF and IFE targets, that is, ignition and propagating thermonuclear burn, is a principal goal of the NIF and LMJ. The more than 15,000 experiments that have been done on Nova and the many thousands more at other ICF facilities around the world (such as Phebus in France, Gekko XII in Japan, and Iskra in Russia) have provided the sound understanding of target physics issues necessary to achieve ignition. This has provided the basis for the specifications of the NIF<sup>8</sup> and LMJ.

The NIF is intended to be an extremely flexible facility. It will have the ability to irradiate both indirect- and direct-drive targets with a variety of pulse formats, including the complicated pulses required for high-gain IFE targets. The NIF should be able to do experiments relevant to all target types and most drivers. *Figure 4* shows current projections for gain expected from a variety of target types.<sup>9</sup>

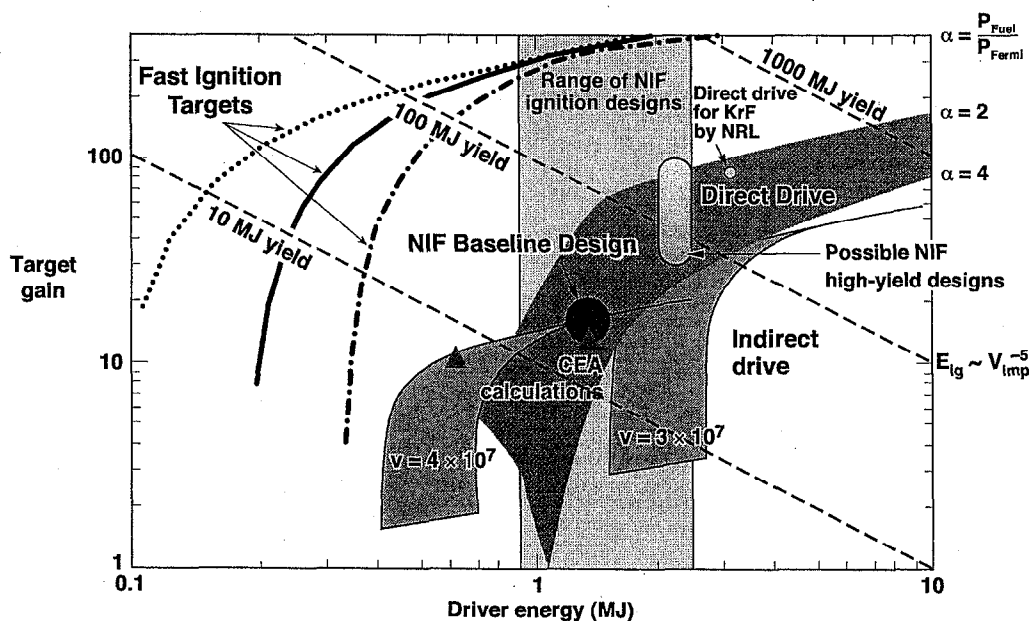


Figure 4. The NIF will map out ignition and gain curves for many target concepts. Velocities ( $v$ ) are in cm/s.

Shown in *figure 4* are sets of performance calculations for various targets. The two bands with the lowest target gain (ratio of energy produced to energy put on target) are the indirect-drive targets.<sup>2</sup> The two indirect-drive sets are labeled with the calculated implosion velocity; the lower velocity driven with about 225 eV and the higher with about 300 eV. The dark circle in the center represents the expected performance of the baseline targets for the NIF. Triangles represent French calculations of their LMJ targets. The central band angling up to the right represents the performance expectations for direct-drive targets with a specific point calculation by the Naval Research Laboratory indicated.

Recent design calculations<sup>10</sup> indicate that it may be possible to obtain higher indirect-drive gains than those calculated for the baseline targets. Gains of 30 to 70 may be possible rather than the 10 estimated for the baseline designs. Higher gains were calculated because of several effects studied recently:

- Lower-power, longer laser pulses deliver more of the NIF's energy to the target.
- Using material mixtures ("cocktails") in the hohlraum wall reduces losses there.
- Slightly larger capsule/hohlraum size increases coupling efficiency to the capsule.
- Longer pulses increase the radiation fraction absorbed by the capsule.
- Reducing the laser entrance hole size reduces hole losses.

Combining all these effects in integrated calculations resulted in gains above 30, and the calculations have not yet been optimized (shown as the vertical oval in *figure 4*).

Finally, three recently calculated curves<sup>11</sup> for possible performance of fast-ignition targets are also shown in *figure 4*. The fast-ignition curves, of course, are based on models that have not yet been validated by experiments. In particular, much work must still be done to determine if the short pulses of the ignition laser can penetrate the plasma created during the implosion of the capsule by the drive laser. However, the remarkably higher gains at lower energy show why we are so interested in this high-risk but high-payoff approach. If it works, an IFE power plant could potentially be economically competitive at a much smaller power plant size than the nominal 1000 MW<sub>e</sub>.

#### 4. THE NIF AND IFE

Achieving ignition and modest energy gain on the NIF will establish the fundamental scientific feasibility of IFE. By this I mean that the NIF will establish that it is feasible to produce energy gain in a facility that costs of order \$1 billion (the same as a typical 1000-MW<sub>e</sub> power plant). But there are many more ways that the NIF will contribute to IFE. NIF development has inspired major laser technology and manufacturing improvements. NIF target experiments will obtain much data essential for IFE targets driven by almost all IFE driver candidates. The NIF will be able to do experiments to gather nuclear effects data needed to design the ETF and IFE power plant reaction chambers. Finally, because of its sheer size, complexity, and similarity, operations on the NIF will give data, validated models, concepts, and experience applicable to IFE development.

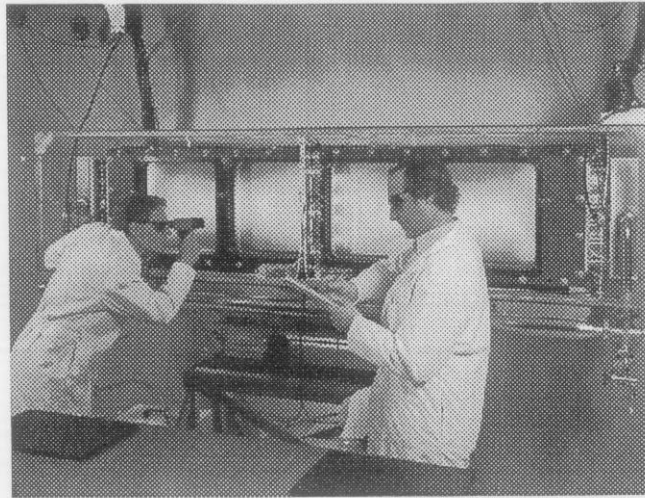
##### 4.1 Laser Technology Development

One of the candidate drivers for IFE power plants is the diode-pumped solid-state laser (DPSSL). While the NIF laser is a flashlamp-pumped glass laser that is not well suited to be an IFE power plant driver, many of the improvements in architecture, component design, and optical manufacturing techniques needed for the NIF also improve the prospects for the DPSSL. Improvement of optical damage thresholds, development of the 40-cm-square aperture plasma electrode pockels cell (PEPC) switch, fast growth of potassium dihydrogen phosphate (KDP) crystals, and faster, lower-cost manufacturing of large-aperture precision optics will have a marked positive impact on the prospects for the DPSSL driver. Finally, the NIF will give us our first experience with diode pumping. While the main amplifier is flashlamp pumped, there is a diode-pumped laser in the preamplifier. It is used there, not for increased efficiency, but for increased stability.

The NIF will include more than 7500 large-aperture (>0.3 m diameter) optical components that will have a total precision optical surface area greater than 3000 m<sup>2</sup>. That is 40 times the area of the precision optics in the Keck telescope. Research at LLNL has resulted in a factor of three increase in the damage threshold of large optics compared to Nova (up to 45 J/cm<sup>2</sup> at 1054 nm, depending on the location). LLNL research with optics vendors has produced new mass production techniques that will lower the cost of each large optic by about a factor of three. The development of the large-aperture PEPC switch (see *figure 5*) allows the laser beams to traverse the main amplifiers four times to more efficiently extract the energy stored there. The PEPC switch and frequency conversion of the 1054-nm light into 351-nm light require very large (about 250 kg) KDP and deuterated KDP crystal boules. For Nova, growth of each crystal boule required approximately 2.5 years. A new, fast-growth technique has grown the necessary full-scale boule in less than eight weeks. This fast growth allows iterative decision making to optimize production yield of these crystals. Table 1 summarizes the advances in optical component production methods that have been developed for the NIF.



Requirements	Features
Aperture	40 cm
Switching efficiency	99%
Average extinction	>300
Minimum extinction ratio	>75
Firing rate	0.2 Hz
Gas pressure	20–150m Torr He
Weight	700 Kg
Electro-optic crystal	KDP
Housings	Anodized aluminum



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Figure 5. The Plasma Electrode Pockels Cell switch allows four passes in the main amplifier, increasing energy extraction efficiency. Here, a stack of four PEPC switches are assembled together in a Line Replacable Unit (LRU) for easy assembly and maintenance.

Table 1. Advances in all areas of optics manufacturing are necessary to meet the NIF requirements at reasonable cost.

Component or process	NOVA Technology	Key technology advancement for the NIF
Laser glass blanks	Batch melting and forming, post-processing	Continuous melting and forming
Crystals	"Low" growth rate; ~1 mm/day	Rapid growth; ~10 mm/day
Fused silica substrates	Round boules, standard size	Optimized boule geometry with higher product yield
Lens/plano optics fabrication	Loose abrasive grinding Planetary polishing	Improved grinding High-speed polishing Deterministic figuring (square optics)
Optical coatings	Large chambers, electron-beam evaporation	Improved process design and control Reduced defects/improve damage threshold
Gratings/phase plates	SiO <sub>2</sub> electron-beam deposited Reactive ion etch (small aperture)	Meniscus coating of photoresist Holographic exposure, wet or reactive ion etch

For a power plant, the higher the driver efficiency in converting electricity to beam energy on target, the lower the target gain that is required for an economical plant. If target gains of 100 are achieved, the driver must be about 10% efficient. It has long been thought by many that solid-state lasers were too inefficient to be good power plant drivers. The efficiency of Nova is about 0.1%. However, the new NIF multipass architecture, combined with the closely compacted square beams, will result in about 1% efficiency for the NIF, an improvement of a factor of ten. By tuning the narrow-band pump frequency of a diode array to the absorption band, DPSSLs promise to improve the NIF's efficiency to 10–15% and to improve the pulse repetition frequency to the 5–10 pulses per second required of a power plant driver, but this has yet to be demonstrated. In a development in parallel with construction of the NIF, LLNL is constructing a 100-J integrated demonstration of the features of a DPSSL driver. The Mercury laser should be ready for testing in 2000 or 2001. These NIF technology developments lower the cost per Joule of putting laser light onto a target by about a factor of 10 compared with Nova. The DPSSL is a now a serious and potentially attractive IFE power plant driver candidate.

#### 4.2 Target Area Technology Development

A NIF target producing 20 MJ of fusion yield will produce  $7 \times 10^{18}$  neutrons (14 MeV), about 3 MJ of x-ray energy and about 3 MJ of debris energy. The fluxes of these at the 5-m wall or at the optical debris shields (at 6.75 m) will be much larger than in any previous ICF facility. The NIF target chamber will function in a very different way than an IFE power plant reaction chamber (e.g., due to the lack of any need to capture the energy produced or clear the chamber in very short times). Nevertheless, the experience and insight gained in designing, building, and operating the NIF target area components to withstand the severe environment created by an exploding target will be invaluable.



The threats to the first wall in the NIF include scattered laser light, target emissions, and debris from objects near the target that are vaporized or produce shrapnel. *Figure 6* shows these threats and the performance criteria for the first wall. Analysis reveals that the first wall's primary function in the NIF is to prevent damage to the final optics due to recondensation of material ablated from the target chamber wall.<sup>12</sup> When material condenses on the final optic, subsequent laser pulses may damage the optic.

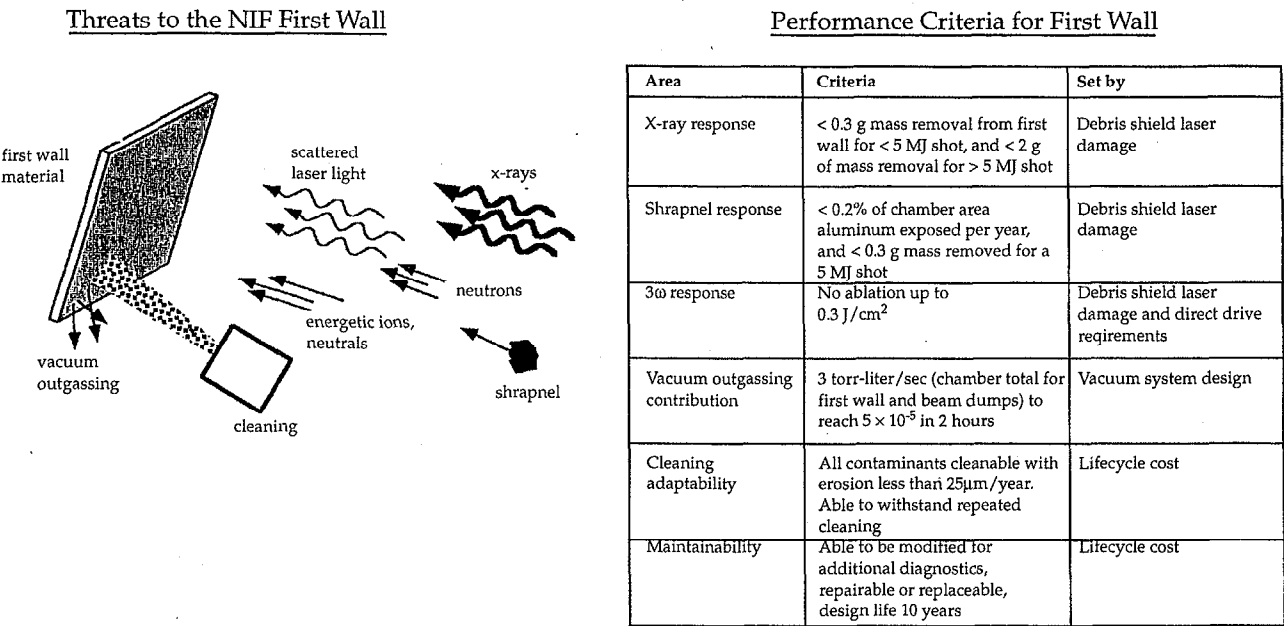


Figure 6. There are several threats to the NIF first wall that set the performance requirements. The first wall's primary function is to prevent damage to the optics due to ablation of the target chamber wall material.

To respond to this first-wall threat, the NIF design team plans louvered first-wall panels of 409 stainless steel. The panels will cover all interior surfaces of the Al target chamber (see *figure 7*). The incoming laser light, x rays, and debris ablate material from the angled portion of the louver. The louvers provide a large surface area for recapturing most of the vaporized material.

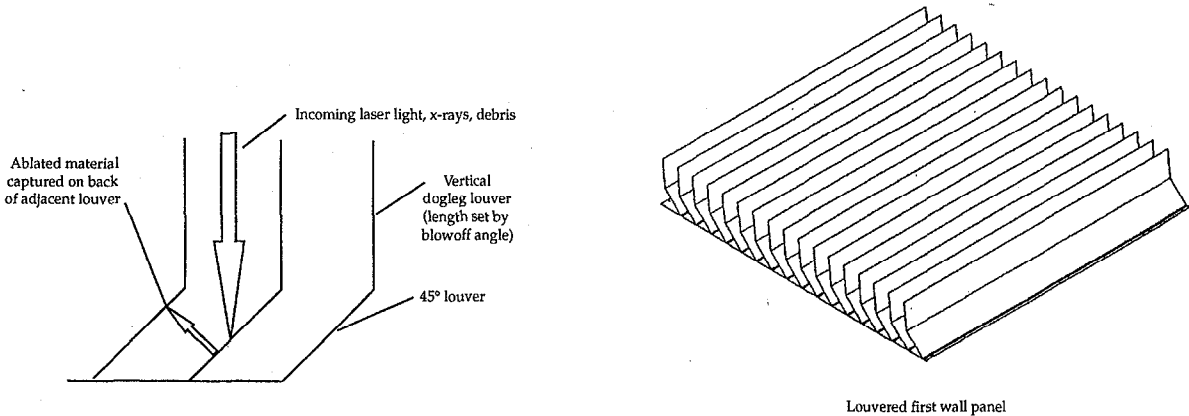


Figure 7. The first wall panels on the NIF are stainless-steel louvers that capture 90% of the material ablated by the scattered laser light and by x rays and debris from the target.

Another issue in the NIF target area is neutron activation (and the associated occupational dose) and its impact upon experiment frequency after high-yield experiments. In the NIF shielding design, aluminum was chosen for the target chamber to reduce the time workers must wait to re-enter the target area after a high-yield experiment. Nevertheless, after a 20-MJ experiment, a five-day stay out time is required to reduce the dose rate to an acceptable level. A recent analysis of dose rate<sup>13</sup>

for the NIF found that a total dose equivalent of less than 10 person-rem/y could be maintained, but this goal would require changing some of the materials used to construct some of the equipment in the target area.

### 4.3 Target Physics Experiments and Target Fabrication Techniques

Three capsule designs are still being considered for indirect-drive ignition experiments on the NIF. All are about 1 mm in radius and have deuterium-tritium (DT) gas in the core, surrounded by a solid layer of DT and an ablator. The three ablators are brominated CH, beryllium-copper, and polyimide. The target fabrication technology being developed to field these targets is providing valuable insight into issues that will have to be solved for the ETF and a power plant. For example, there has been rapid progress in techniques for producing the plastic or beryllium shells of the proper surface finish, filling the capsules, producing the solid DT shell by beta-layering, and measuring the ice roughness. Figure 8 shows examples of the cryo layering, measurements of the ice roughness, and two of the ablator shells. A hohlraum design and cryostat incorporating the necessary support for cryogenic targets are being developed to keep the ice layer at 18–19 K with a temperature uniformity of  $\pm 15 \mu\text{K}$ . These target fabrication developments and the experience using cryogenic targets on the NIF will provide useful data and insights into how to perform this function at the ETF or in a power plant.

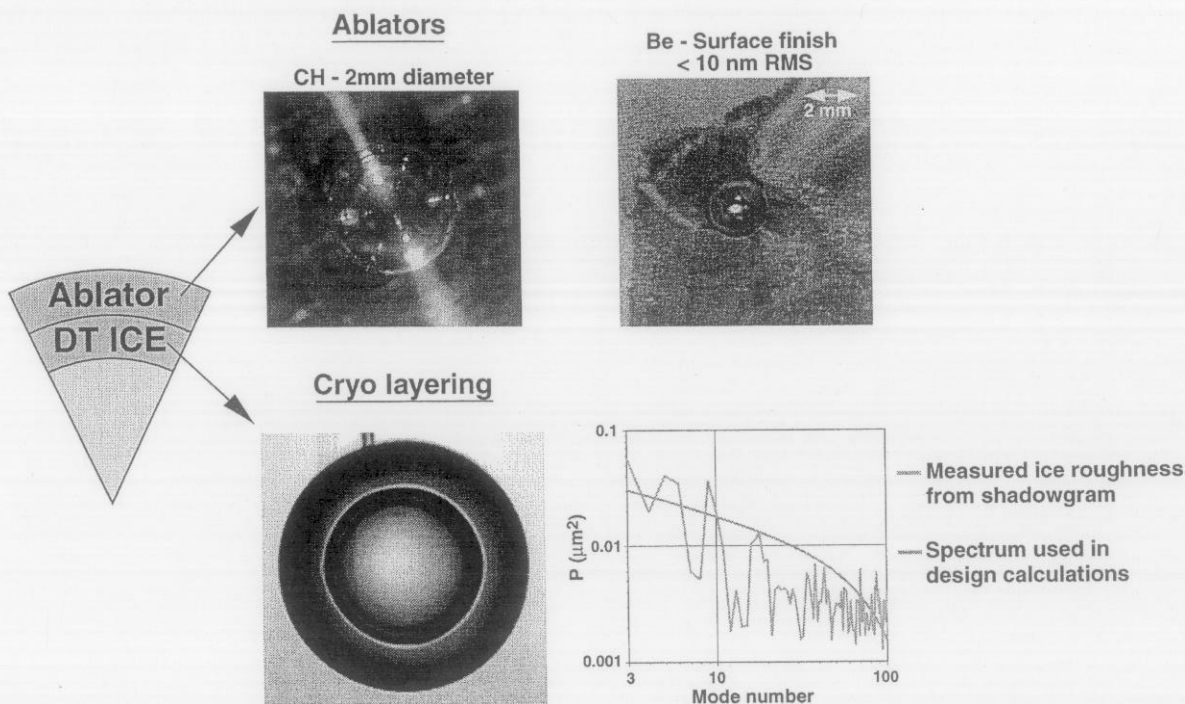


Figure 8. Target fabrication techniques developed for making and supporting NIF ignition targets provide useful insights into how to accomplish this function in the ETF or an IFE power plant.

NIF ignition targets are expected to achieve ignition and burn propagation. This will result in an energy gain ( $G$ ) on the NIF of 1–10. For IFE, gains of 30 to more than 100 are needed depending upon the energy conversion efficiency of the driver ( $\eta$ ). An  $\eta G$  product greater than 10 is needed for an economic power plant.<sup>1</sup> Therefore, it is important to relate the ignition target results expected on the NIF to the higher gains needed for IFE.

To obtain high gain, ICF targets depend upon compressing all the fuel to high density, but heating only a small “hot spot” to high temperature and ignition. The burning hot spot, in turn, ignites the inner portion of a layer of cold compressed fuel by depositing some of the alpha particle energy produced in the thermonuclear reactions. This results in a self-sustaining thermonuclear burn wave that propagates outward through the entire cold-compressed fuel layer. The NIF ignition targets have been designed to obtain ignition in the same way so that both ignition and burn propagation are demonstrated. Thus, all that would be necessary to obtain high gain would be to compress more cold fuel so that the burn wave would propagate further before going out. The similarity in target physics between the NIF ignition targets and high-gain targets is shown in Figure 9.<sup>14</sup>

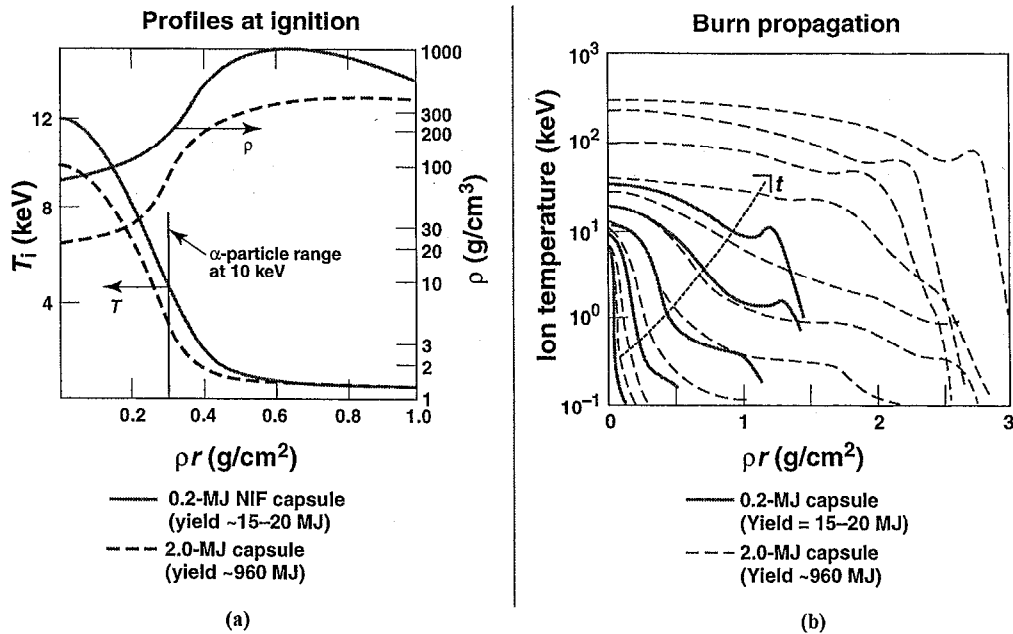


Figure 9. Ignition and high-gain capsules have very similar ignition and burn propagation physics. The left figure (a) shows the temperature and density profiles at ignition for a NIF ignition capsule (0.2-MJ) and for a high-gain capsule (2.0-MJ). The right figure (b) shows how the temperature profile changes with time ( $t$ ) for both capsules.

Figure 9(a) shows the temperature and density profiles at ignition of both a NIF ignition capsule (solid lines) and a high-gain capsule (dashed lines). The 0.2-MJ and 2.0-MJ numbers associated with the ignition and high-gain capsules respectively are the amount of drive energy absorbed in the target capsules. The hot spot is that region within the  $\alpha$ -particle range (0.3 g/cm<sup>2</sup>). Temperatures are high and densities low in this region, but the key is that the hot spot is one  $\alpha$ -particle range thick, and thus, the hot spot is self-heated to higher temperature (about a factor of two). Figure 9(b) shows more of the temperature profiles at later times. The  $\alpha$ -particles start the burn propagation in the cold fuel. NIF ignition capsules will have a  $\rho r$  of about 1 g/cm<sup>2</sup> and, therefore, the burn front goes out when it reaches these values. High-gain capsules will have a  $\rho r$  of about 3 g/cm<sup>2</sup> and, therefore, the burn front will continue to propagate, producing more yield and gain by the same physical process to be demonstrated in the NIF ignition capsules. All centrally ignited ICF capsules operate in this manner, and establishing this central hot spot (with its associated high convergence ratio) is what places severe requirements on flux uniformity and capsule smoothness. It is harder to ignite and burn small capsules than large ones (the convergence ratio must be larger to obtain the necessary  $\rho r$  for  $\alpha$ -particle deposition). (Fast-igniter targets, on the other hand, establish a hot spot at the edge of the cold-compressed fuel and, therefore, have the potential to reduce the uniformity and smoothness requirements.) Thus, successful ignition on the NIF will provide high confidence that high-gain IFE targets can be successful.

For IFE it is also important to verify the shape of the gain curves (Figure 4). Calculated gain curves have a noticeable change in slope as a function of drive energy. Power plant system studies use gain curves (and many other subsystem performance curves) to determine the best operating point (e.g., lowest cost of electricity) of the power plant. This determination, in turn, drives the development programs of the various other components. Therefore, it is important to determine the real shapes of the gain curves for various types of targets so that the IFE R&D priorities can be assessed more accurately.

While the NIF has a laser driver, experiments can be done on the NIF that test the target physics relevant to most candidate IFE drivers. For example, Figure 10 shows a NIF target compared to a heavy-ion fusion target. Issues of hohlraum energetics, symmetry control, and capsule implosion physics are similar enough that specific experiments on the NIF can be designed to examine issues important to targets driven by other drivers. In such experiments, target physics differences would have to be accounted for. For example, the temperature in the ion-beam hohlraum rises more slowly compared to the temporal profile of the energy deposition than for a laser target. Therefore, in NIF experiments, the temporal profile of the laser pulse would have to be changed to produce a thermal profile in the hohlraum closer to that in a heavy-ion target. These differences can be accommodated in the NIF. Therefore, the NIF will be able to do target physics for most IFE driver types. Only such driver types as the Z-pinch or magnetized target fusion would be difficult to simulate in the NIF.

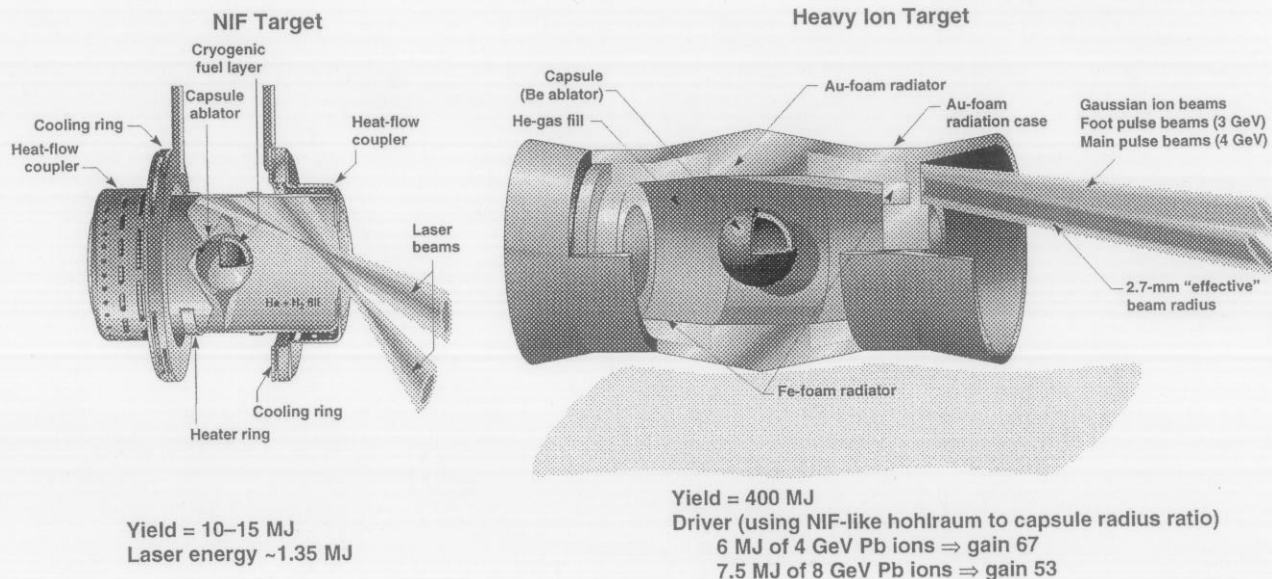


Figure 10. The physics issues for ion-beam and NIF targets have much in common.

Much effort is being devoted at present into making sure that the NIF targets will be smooth enough and that the NIF driver will create a uniform flux on the capsules so that the central hot-spot ignition has the highest probability of succeeding. Advanced three-dimensional calculations, as shown in *figure 11*, are being done to simulate the effects of instability growth on the capsule performance. After ignition is achieved on the NIF, IFE will want to study the trade-off between target performance and fabrication and driver uniformity specifications. In a power plant, the tighter these system performance specifications, the higher the cost of the components that must mass produce the targets or must inject them and steer the beams to them. Therefore, the real relationship between these specifications and target performance must be understood, and the NIF can provide data to resolve the issue. It can also explore advanced target concepts that may achieve higher target performance once the fundamental understanding of ignition and burn propagation has been tested with data from burning targets.

3-D simulation includes modes  $l = 15-200$

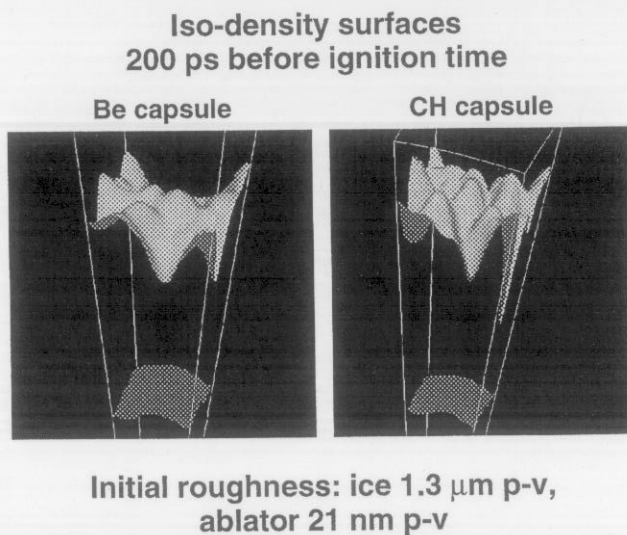
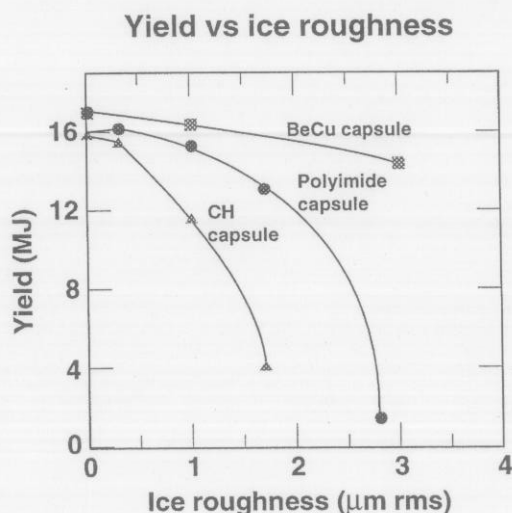


Figure 11. 3D simulations are being performed to establish capsule fabrication and flux uniformity requirements for NIF ignition capsules.

#### 4.4 Target Area Technology Experiments

There have been several IFE community workshops to discuss specific experiments the NIF can do to resolve various IFE development issues.<sup>7,15</sup> In all, it was recognized that NIF ignition and nonignition experiments can provide sources that would allow examination of some of the target area issues for design of the ETF or a power plant. The  $7 \times 10^{18}$  neutrons produced in an ignition experiment can be used to examine how isochoric heating in liquid walls causes liquids to explode and can help estimate the size distribution of the resulting droplets. This is necessary in evaluating vaporization and recondensation issues (and, hence pulse repetition capabilities) for several power plant concepts.

NIF experiments for IFE chamber issues can also be done without ignition. For some time it has been recognized that the NIF laser beams could be directed upon targets such as foil disks or gas bags containing a mixture of gases to produce very intense x-ray (and debris) sources. The emissions can be used to study many first-wall effects such as material vaporization, shock creation, and shrapnel production. These experiments can also study proposed mitigation techniques such as gas puffs to protect final optics. Figure 12 shows one concept for how such experiments could be conducted on the NIF.<sup>16,17</sup>

These minichambers could also be used to study how the presence of post-shot gases affect target injection accuracy and next-laser-pulse propagation to the target. The NIF laser could also deliver a series of pulses in separate clusters fired 200 ms apart to begin to see pulse-rate effects.

#### The NIF, even without ignition, will allow testing of IFE chamber components to x-ray and debris loads

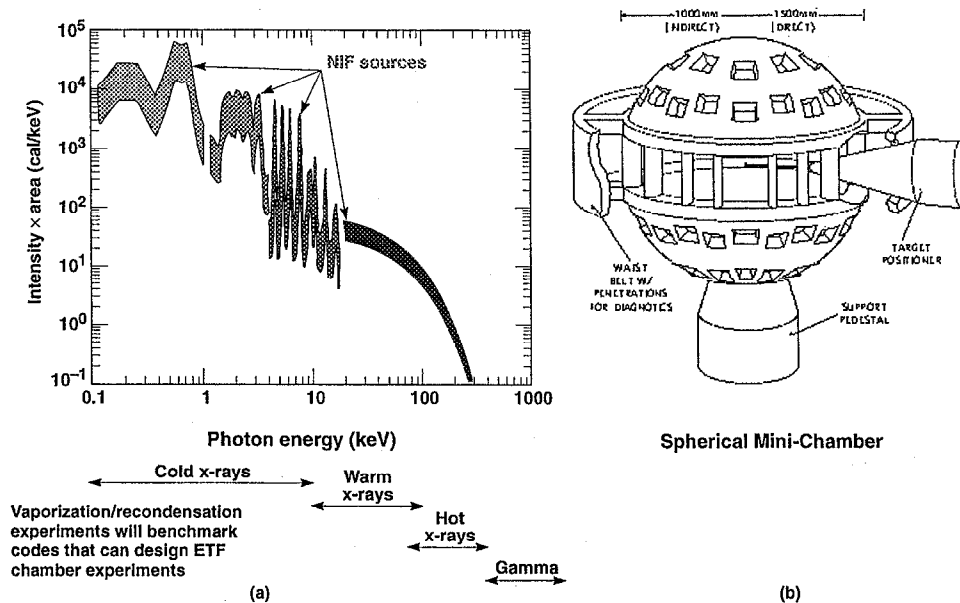


Figure 12. Nonignition NIF targets could convert laser energy into x rays and debris, which simulate the post-shot power plant chamber environment inside a minichamber placed at the center of the normal NIF target chamber. Figure 12 (a) shows the x-ray spectra that could be created and (b) shows the inner chamber arrangement.

#### 4.5 Operating Experience

As pointed out at the beginning of this paper, the scale and complexity of the NIF is similar to that of a power plant. Many of the NIF's basic functions (e.g., driver beam creation and conditioning, beam alignment on target, dealing with high-pulse radiation) have analogous functions in a power plant. Therefore, some insight can be gained from operations at the NIF regardless of what mission the particular experiments are designed to satisfy. We will gain data on reliability, availability, and maintainability of large, complex solid-state laser systems (although, of course, careful selection of what is relevant and what is not would be important). The experience gained in keeping the final optics as free as possible of recondensed material and in how these optics are maintained will be useful. The methods used and experience gained in fabricating, maintaining, and handling cryogenic targets will be very important for future IFE development. Verification of computer codes, for example those dealing with prompt radiation and activation, will allow those codes to be used for design of the ETF with more confidence. The data collected can influence design and assessments of ETF and power plant safety systems and issues.

These are just a few of the areas of operating experience currently considered. This topic should be explored more fully as the NIF transition to operations approaches so that more useful data can be collected.

## 5. SUMMARY

In this paper the author has presented his views (based upon the work of many scientists and engineers in the field) about some of the important issues in the development of IFE. Two target ignition facilities are now under construction—the NIF at the LLNL in the United States and LMJ at CESTA near Bordeaux, France. While both facilities are being built for national security purposes, both will contribute a great deal toward the development of IFE. The gain to IFE has already begun in the development of components and optical manufacturing techniques. Experiments and operations on both facilities will provide valuable data, tools, and experience that will contribute greatly to the progress in IFE. International collaboration on the NIF and LMJ can greatly enhance the utility of these facilities for the application of inertial fusion science and technology.

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This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under contract No. W-7405-Eng-48.